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Microgrids in active network management – part II: System operation, power quality and protection

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ABSTRACT

The development of distribution networks for participation in active network management (ANM) and smart grids is introduced using the microgrid concept. In recent years, this issue has been researched and implemented by many experts. The second part of this paper describes those developed operational concepts of microgrids that have an impact on their participation in ANM and in the requirements for achieving targets. Power quality is the most challenging task in microgrids, especially when the system switches from normal parallel operation (grid-connected mode) to island operation. Indeed, following planned or unplanned transitions to island mode, microgrids may develop instability. For this reason, the paper addresses the principles behind island-detection methods, black-start operation, fault management, and protection systems, along with a comprehensive review of power quality. Finally, island detection and the other topics are summarized with a flowchart and tables.

Contents

1. Introduction

Future distribution networks will require completely novel smart grid concepts [1–3]. In this regard, flexible microgrids (MGs) that are capable of intelligently operating in both grid-connected and island modes are required [4–6].

In recent years, several control devices have also been developed to improve the integration of MGs [7–9]. The variations in power generation, interconnection, and electrical interface may constitute barriers to achieving an optimal system for connecting distributed energy resources (DERs) to the grid [10–13].

In the first part of their paper [14], the authors proposed adapting the IEC/ISO 62264 standard to the MG, virtual power plant (VPP), and storage system. The standardization was explained

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Nomenclature

AFD	Active Frequency Drift
AMM	Automate Meter Management
APF	Active Power Filter
APS	Automatic Phase Shift
ARPS	Adaptive Reactive Power Shift
DER	Distributed Energy Resource
DG	Distribution Generation
DMS	Distribution Management System
DL	Dispatchable Load
ESS	Energy Storage System
LC	Local Control
LV	Low voltage
MCB	Miniature Circuit Breaker
MGs	Microgrids
MGCC	Microgrid Control Centre
MMS	Microgrid Management System
NDZs	Non-Detection Zones
NSCI	Negative Sequence Current Injection
PCC	Point of Common Coupling
PF	Positive Feedback
PI	Proportional Integral
P/Q	Active and Reactive Power
RESs	Renewable Energy Sources
ROCOF	Rate of Change of Frequency
SCADA	Supervisory Control and Data Acquisition
SFS	Sandia Frequency Shift
SMS	Slip Mode Frequency Shift
SOC	State of Charge
SVS	Sandia Voltage Shift
THD	Total Harmonic Distortion
U/O FP	Under/Over Frequency Protection
U/O VP	Under/Over Voltage Protection
UPS	Uninterruptible Power Supply
UPQC	Unified Power Quality Compensator
UTSP	Unified Three Phase Single Processor
VPF	Voltage Positive Feedback
VU	Voltage Unbalance

on five levels: *level zero* (the generation process), *level one* (the process of sensing and adjusting generation), *level two* (monitoring and supervision), *level three* (maintaining and optimizing), and *level four* (market structure and business model). Based on the investigation in the first part, the tertiary control level is disabled when the MG switches to island mode [15]. Hence, the first objective of the present paper (second part) is the comprehensive investigation of island-detection methods in the MG.

As presented in [16], an MG operates normally in parallel with the utility grid. However, the transition to island operation may occur as a result of a permanent fault in the main grid, or due to an intended disconnection. This is why, in the event that the transition is unsuccessful (for example, due to a fault during transition), a blackout occurs – in which case, the black-start strategy should be used. In Fig. 1, the operational modes of MGs are presented. In this sense, the restoration of service is performed first by disconnecting the distribution generation (DG) units, and thereafter by reconnecting them in a controlled way.

As aforementioned, MGs need to be able to operate intelligently in both grid and island mode [17–19]. Thus, the great challenge is to combine all the various power electronics, communication technologies, interfaces, and energy-storage mechanisms [20,21]. Moreover, stability and voltage regulation are the greatest challenges to the integration of renewable energy into the main network. Hence, power quality for the customer, which is supported through the MG in both operational modes, is very important [22–24].

The protection system is another major challenge to MG operations [25–27]. The protection system for MGs must also function in both grid-connected and island mode [28,29]. As discussed by Justo et al. [30], the principle of protection in conventional grids and in MGs cannot follow the same approach. The responsibility of the protection relay when a fault appears in the main grid is to isolate the DG units and loads, and move to island-mode operation. However, the relay removes the smallest part of the system in which the fault occurs during the island operation.

In order to cover all these issues, the second objective of this paper is a comprehensive literature survey of power quality, fault management, black-start operation, and protection. The investigation provides information on the status of and advances in MG principles from the viewpoints of island and grid-connected modes.

Island operation and detection techniques are dealt with in Section 2. Power quality is presented in Section 3. Microgrid black-start operations, monitoring, and fault management are discussed, along with protection, in Sections 4–6 respectively. Finally, the literature survey concludes in Section 7.

2. Island-mode detection and operation

A microgrid should deliver high-quality power without interruption to customers through the local DG units [31,32]. Their performance in island mode should be based on standards, such as IEEE Std. 1547, UL 1741 (the anti-islanding test configuration) and IEC 61727 [33,34]. However, some countries use different standards for evaluation, such as DIN VDE 0126 in Germany [35] and C22.2 no. 107.1-01 in Canada [36]. The various requirements for the operational limits of voltage and frequency according to the two most important standards for island detection (the IEC and the IEEE) are shown in Table 1. Island-detection methods are generally classified into two main types of techniques: the remote and the local [37,38]. Remote techniques are centralized methods associated with island detection on the utility side. Their high performance and applicability are their advantages, but they are not economical when compared with local techniques [39]. Local techniques involve island detection on the DG side, and can be classified into three different types [40–43]: passive, active, and hybrid methods. Anti-island-detection methods are evaluated through the non-detection zone (NDZ). The NDZ is defined on the basis of an operation failing at the right time on account of loading conditions [44–46]. A broad NDZ is the main disadvantage of local techniques [47], and the largest NDZ area occurs with the passive methods [48]. Thus, the passive methods cannot support high DG penetration. However, the active methods make up for some of the disadvantages, and so some of the methods may support multiple DGs [45,49].

As presented by Mahat et al. [45], hybrid methods are the result of combining both the above detection techniques. In hybrid methods, the active technique is implemented only when islanding is detected by a passive technique. Fig. 2 (which is based on [50]) shows the classification of methods with their advantages and disadvantages.

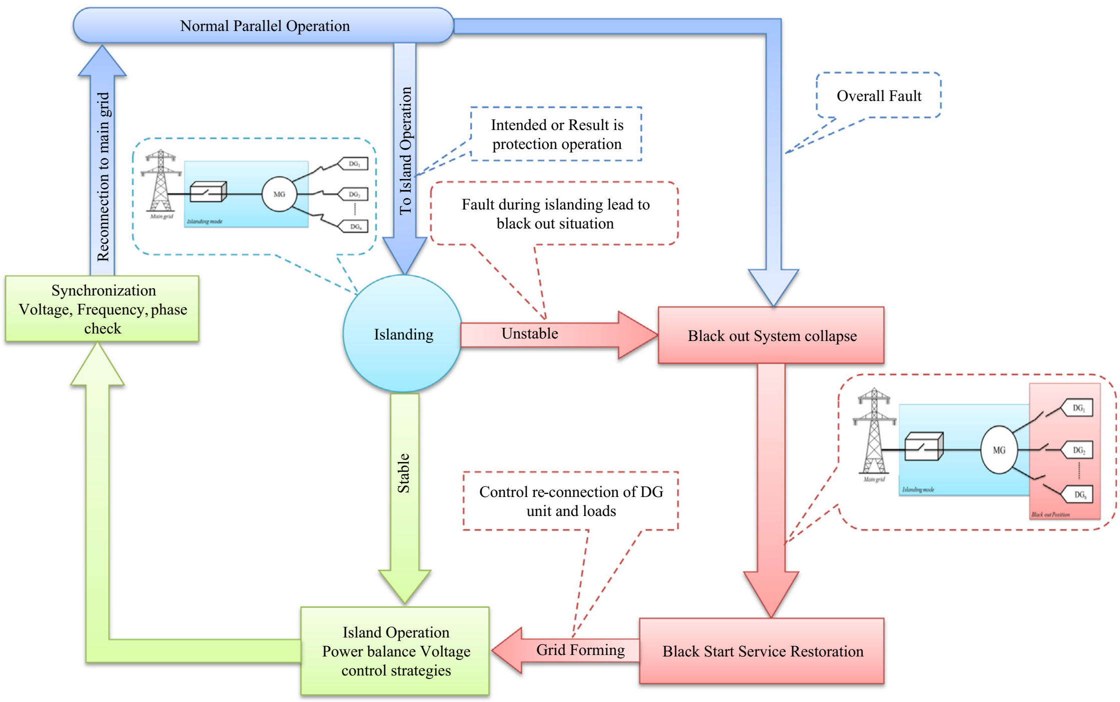


Fig. 1. Operational method of microgrid [16].

Table 1
Frequency & voltage operation limits for IEEE 1547 and IEC 61727. std.

IEEE Std		IEC Std.	
Frequency limitation	**Clearing time (S)**	**Frequency limitation**	**Clearing time (S)**
$f\langle 59.3$	0.16	$f\langle 59$	0.1
$f\rangle 60.5$	0.16	$f\rangle 61$	0.1
Voltage limitation (V_{rms})	**Clearing time (S)**	**Voltage limitation (V_{rms})**	**Clearing time (S)**
$V\langle 0.5v_n$	0.16	$V\langle 0.5v_n$	0.1
$0.5v_n\langle V\langle 0.88v_n$	2	$0.5v_n\langle V\langle 0.85v_n$	2
$1.1v_n\langle V\langle 1.2v_n$	1	$v_n\langle V\langle 1.1v_n$	2
$1.2v_n\langle V$	0.16	$1.1v_n\langle V\langle 1.35v_n$	0.05

2.1. *Local techniques*

2.1.1. *Passive methods*

In the passive methods, voltage, frequency, and the system's harmonic distortion parameters are continuously monitored. Indeed, these parameters will vary as the mode of MG changes [51,52]. Hence, a suitable setting for maximum and minimum allowed variation improves the ability to distinguish connections [53]. The most common passive methods are discussed by Zeineldin et al. [14]. The methods do not damage the system, and they enable high-speed relay operation. However, these techniques suffer from relatively large NDZ [45]. In other words, if the variation in the monitored parameters does not exceed the permitted values (which sometimes come from the standards), then the system does not transfer to island mode [35]. A hybrid method is proposed to solve this problem, and will be discussed later in this paper. Moreover, some important characteristics of the popular techniques are collected in Table 2. These include the monitored parameters, advantages and disadvantages, the NDZ interval, the detection speed, and other details [54–56].

As mentioned, the disadvantage of passive island-detection techniques is the large NDZ. To reduce it, the method can be combined with one of the local active anti-islanding techniques in a hybrid method. A hybrid passive method has been proposed by Jang et al. [57], based on monitoring the voltage unbalance and the total harmonic distortion (THD). This approach enhances the performance of the passive methods, and will be explained in the section about hybrid techniques.

2.1.2. *Active methods*

The second type of anti-island-detection method is based on feedback techniques and on monitoring the response to disturbances deliberately injected into the circuit [58]. Indeed, the active method has the same principle as the control mechanism, and detects the variation of both frequency and voltage at the point of common coupling (PCC) [44,59].

The technique has a smaller NDZ, compared with the passive method; however, it can lead to a degradation in the power quality of the system [53,60–62]. A complete review of these methods is presented by Kunte et al. [59]. An active island-detection strategy

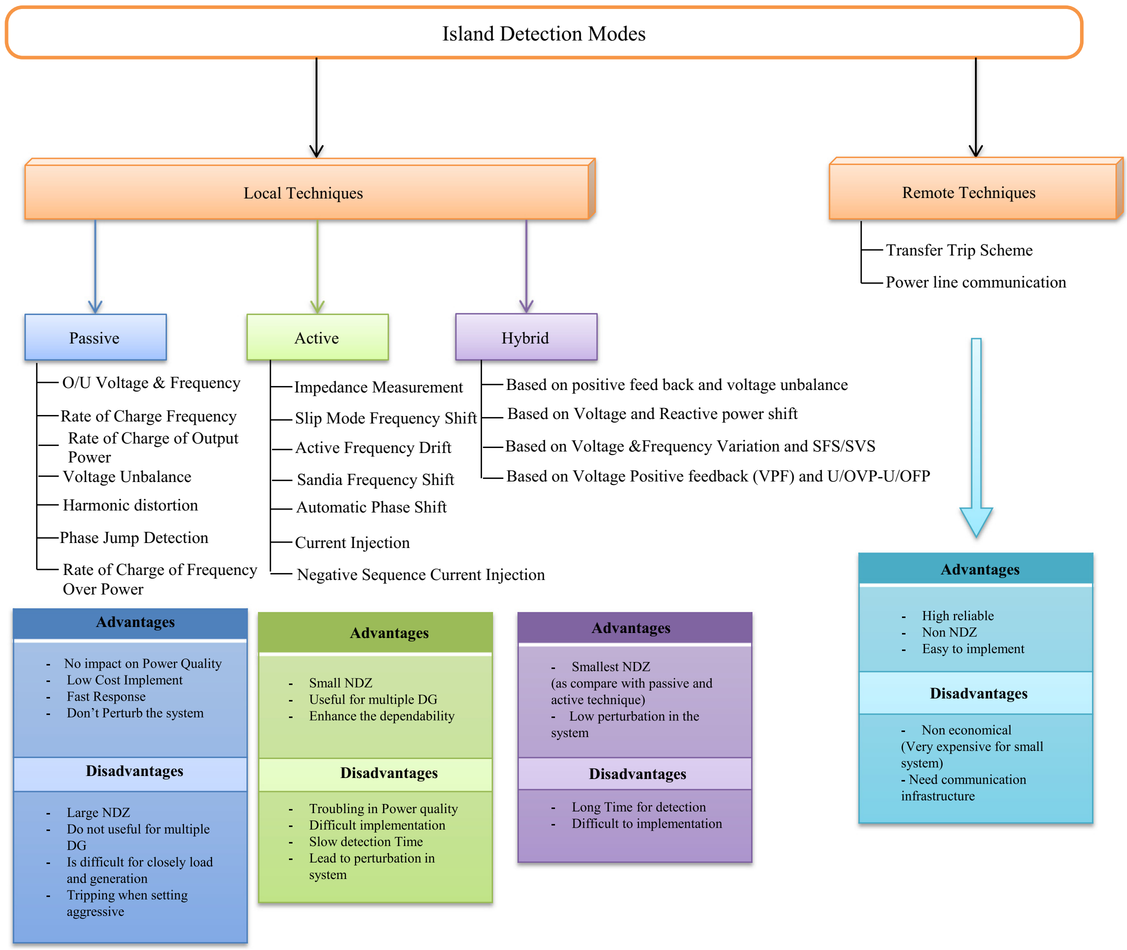


Fig. 2. Classification of island-detection methods [50].

that relies on equipping the DG interface with a Q–f characteristic is presented in [44]. As with the passive method, some important characteristics of popular techniques, including monitoring parameters, advantages and disadvantages, the NDZ interval, the detection speed, and other details are presented in Table 3 [59,63,64].

2.1.3. *Hybrid methods*

Hybrid techniques of island detection are the result of combining a passive method with an active method [36]. Indeed, the passive technique has operational priority in these island-detection methods, and the active methods operate after passive detection [46]. The main advantage of hybrid methods is that they minimize NDZs, as compared with the other two local techniques. Due to this significant advantage, hybrid techniques are much more effective for island protection. The most common hybrid methods are presented in [36,45,49,65,66], and Table 4 illustrates their advantages and disadvantages, and other important issues regarding this class of techniques.

Moreover, with respect to the definition of passive, active, and hybrid techniques, Fig. 3 shows a complete algorithm for local island-detection methods, developed on the basis of [50]. As can be seen in this figure, the passive and active methods share some common features. Indeed, the differences lie in measuring and monitoring: in passive methods, only measuring occurs, while active methods are based on signal feedback. Hybrid methods combine both passive and active methods in these measuring and monitoring parts.

2.2. *Remote techniques*

Following the island-detection classification methods shown in Fig. 2, remote techniques form another detection group. The design of such techniques is based on a communication link between the distributed generator and the main grid [39]. Higher reliability is the main advantage of this method over local techniques [67]. However, the method is uneconomical, as it is expensive to implement. The most popular remote island-detection methods are presented by Xu et al. [23], Mahat et al. [45] and Kunte [59]. The details of these methods, along with their advantages and disadvantages, are summarized in Table 5.

There are many factors that should be considered in selecting the island-detection method. Economic issues, in particular, have always been important [59]. As mentioned, island detection is very significant in MGs because of its strong relation with the MG control and storage system. Hence, remote control is more popular in smart grids and MGs, even when the additional costs are taken into account.

In conclusion, many techniques have been developed for island detection with single DGs. Yet when many DGs are placed in parallel in an MG, the NDZ increase is notable. The solution to this is to use a microgrid control centre (MGCC), thus considering the whole MG as a 'single DG block.' Similar techniques are then implemented at the PCC with the MGCC. Moreover, for both island detection and island operation, a communication and intelligence interface is needed to connect the grid and the island into the MGCC. Indeed, all decisions concerning active or reactive power

Table 2
Passive method island detection characteristics.

Island detection mode	Monitored parameter	Advantages	Disadvantages	NDZ	Single DG	Multiple DG	Implementation/Speed
O/U Voltage/Frequency	– Frequency – amplitude Voltage	Avoid undesired DG tripping	Slow Detection Large NDZ	Large	✓	–	Simple/Slow
ROCOF	Voltage wave form	Highly reliable when there is large mismatch in power	Reliability Fail to operate if DG's capacity matches with its local load	Large	✓	–	Simple/Normal
Change Impedance	Impedance	Small NDZ (Compared to other passive methods)	– No effect if changing be small – Effectiveness decrease the number of connected inverter	Small	✓	–	Simple/Normal
Voltage unbalance	– Voltage magnitude – phase angle – frequency change	Easy Implementation	NDZ effective in small changing	Large	✓	–	Simple/Fast
Harmonic distortion	Total harmonic distortion of grid voltage	Effectiveness does not change where there are multiple inverters, but of course may need to coordination	– The method fail for high values of quality factor – Sensitive to grid perturbation – Threshold is difficult to set	Large	✓	–	Simple/Normal
Phase jump detection	Phase difference between voltage at the PCC and inverter output	Easy Implementation	– Let to nuisance tripping – Threshold is difficult to set	Large	✓	–	Simple/Fast

control, island detection, operation, and storage systems are managed by the MGCC. The decision to switch to island mode, and also to resynchronize after islanding, is thus based on measurements of MGCC on both sides of interconnection mode [68]. As mentioned in the introduction, this study is primarily a technical comparison. However, economic comparisons constitute another important dimension, and are discussed in [39,69].

3. Power quality

As demands on DG units continue to increase [70], power quality, stability, and power balancing are crucial issues for microgrids and smart grids [71]. Moreover, improvements in performance, telecommunications, operations, and regulation – as well as in network planning – are all very significant in designing smart grids [72]. Based on the council of European energy regulators (CEER) [72,73], the coverage of power quality in MGs can be divided into three main parts, as shown in Fig. 4.

Recently, researchers have tried to minimize the most significant issues relating to the quality of electricity in distribution systems, such as harmonic current and unbalancing conditions. Indeed, the evaluation of power quality is based on IEEE 519-1992, IEC 61000-4-30 [74], and EN50160 [75]. In these standards, the THD of the voltage and the individual voltage distortion are limited to 5% and 3%, respectively, in distribution networks below 69 KV [76,77]. Moreover, according to IEEE Standard 1547.2-2008, the voltage fluctuation is limited to $\pm 5\%$, as renewable energy sources (RESs) are parallel to low-voltage systems [78].

With electrical storage and distributed generation, power quality could be maintained in much the same way as with uninterruptible power supply (UPS) systems [79].

Moreover, electronic inverters are also used for compensation [80]. Such devices are able to generate reactive power, supplying reactive loads useful in dealing with unbalanced loads and the generation of harmonic currents. Indeed, the main role of an interface converter is to control power injection [81]. Beside the energy storage system in island-operation mode and also inverter, active power filters (APFs) are also effective elements for improving the power quality [82].

As discussed by Savaghebi et al. [83], power-quality problems are of two main types: voltage unbalance and harmonics. As long as a single-phase load is connected to the MG, voltage unbalance can occur in the MG [84]. Indeed, some of the equipments in MGs – such as power converters and induction motors – suffer from voltage unbalance in the system [85]. Using series and shunt APFs is a solution to this problem of unbalanced voltage [86]. In this method, compensation is provided by injecting negative sequence voltage (respectively, current) into the power distribution line for the series (respectively, shunt APF) method [87–89].

Indeed, the main role of the DG inverter in regulating the phase angle and the amplitude of the output voltage is to inject the reactive power or observe it. Thus, another method for optimizing power quality is the control strategy which is presented by He et al. [90]. The use of a two-inverter structure approach for control is described in [91,92], and is similar to a series-parallel APF – one being connected as a shunt and the other in series with the grid [83].

The injection of negative-sequence current by the DG is another method of compensating for voltage unbalance, as discussed in [93]. However, as it uses much of the interface's converter capacity for compensation, the method is not effective under severely unbalanced conditions. It may even have negative effects on the active and reactive power generated by the DG.

Cheng et al. [94] presented another method for compensating for voltage unbalance in MGs. This involves generating a reference

Table 3
Active method island detection characteristics.

Island detection mode	Monitored parameter	Advantages	Disadvantages	NDZ	Single DG	Multiple DG	Implementation /Speed
Impedance measurement	Impedance	– Highly reliable – Dependability	Poor results for multiple inverter connected	Small	✓	_	Simple/Fast
Impedance detection at specific frequency	Harmonic voltage	Easy implementation	nuisance trip problem in multiple inverter case	Small	✓	_	Simple/ Relatively Slow
SMS	Phase of PCC voltage	Effective in multiple inverters	Requires a decrease in the power quality of the DG inverter	Relatively Slow	_	✓	Medium/Slow
AFD	Chopping factor drift between current and Voltage	Strong dependability	appropriate chopping fraction to not reach harmonic limit	Large	_	✓	Complex/ Medium
SFS	Frequency Drift with positive feedback	Most effective method in active technique	Difficult Implementation	Very Small	_	✓	Complex/ Relatively fast
SVS	Voltage amplitude	Easy to implement	In positive feedback operation power quality slightly reduce	Very Small	_	✓	Simple/Fast
APS	Frequency of terminal Voltage	Alleviates the problem for AFD SMS	For non -linear load have large inertia	Just in non-linear load	_	✓	Medium/Fast
Current injection	Disturbance signal through d or q axis controller	Fast response (Compared to other active methods)	Fail for loads having value quality factor more than 3	Very small	_	✓	Complex/Fast
NSCI	Negative sequence voltage	Can be used in both single DG unit and multiple DG unit	No NDZ	None	✓	✓	Complex/Fast

Table 4
Hybrid island detection characteristics.

Island detection mode	Monitored parameter	Advantages	Disadvantages	NDZ	Single DG	Multiple DG	Implementation/ Speed
PF and VU	Three phase voltage continuously	Encompass small changing	Long time for detection	Very small	✓	_	Medium/Slow
Voltage and reactive power	Voltage variation and reactive power shift	Low perturbation	Long time for detection	Very small	✓	_	Medium/Slow
U/O Voltage and Frequency with SFS or SVS	– Voltage amplitude – Frequency Shift	Most effective on hybrid method	Long time for detection	Very small	✓	_	Medium/Slow
VPF and U/OVP-U/OFP	Voltage and frequency	Can be used in multiple DG units	Long time for detection	Very small	_	✓	Medium/Slow

for a negative-sequence conductance based on the negative-sequence reactive power. There is in fact a trade-off between voltage regulation adequacy and the efficiency of unbalance compensation. To cope with this, [83] proposes to directly change the voltage reference in order to compensate for the voltage unbalance in an MG.

As mentioned earlier, THD is another power quality problem that arises due to the tradeoff between current with the main grid and the voltage of the local inverter loads [95]. Hence, a cascaded control structure consisting of an outer-loop current controller and an inner-loop voltage controller has been proposed by Zhong [95]. Indeed, the concurrent determination of the low THD for the grid current and of the voltage of the local load inverter is the goal of the method.

Truly, power quality in MGs can be enhanced with two complementary approaches. These are dedicated APFs and the use of the capability of existing DGs. The general scheme of power quality in MGs – based on the IEC 62264 standard (introduced in the first part of this paper) – is shown in Fig. 5. Indeed, primary power quality includes controlling a DG. Moreover, the responsibility of secondary control is to coordinate the power between the DGs and to support the load with a high-power quality level. The scheme consists of different parts: dedicated units, using DG units as parallel APFs, and back-up support connected to the main grid through a back-to-back converter. In [96] the back-to-back converter was used to test for the presence of power quality problems in grid-connected MGs, and to mitigate them. As mentioned in the Introduction and in Section 2, the target of this paper is a technical evaluation of microgrids. However, economic issues are also important in finding the best methods to improve power quality. The economic evaluation of power quality is discussed by Lin et al. [97] and McGranaghan et al. [98].

4. Black-start operation

Power interruptions can appear in the whole system or in a single part, and can arise from unplanned events in the MG [99]. During island-mode operation, this situation can lead to a blackout [100]. The stability of the system has then been compromised, and all DG units are disconnected from the MG [101–103].

The process of restoring the system is called a black-start [101]. Power management, balancing, and voltage control are the responsibilities of the black-start restoration service, which is embedded in the MGCC. As presented by Lopes et al. [104], black-start operations are divided into two significant categories, as dictated by the availability and sequence of the restoration strategy. The first category is based on bidirectional communication links, the ability to receive the most recent information from microsources (MSs), and the ability to disconnect loads [105].

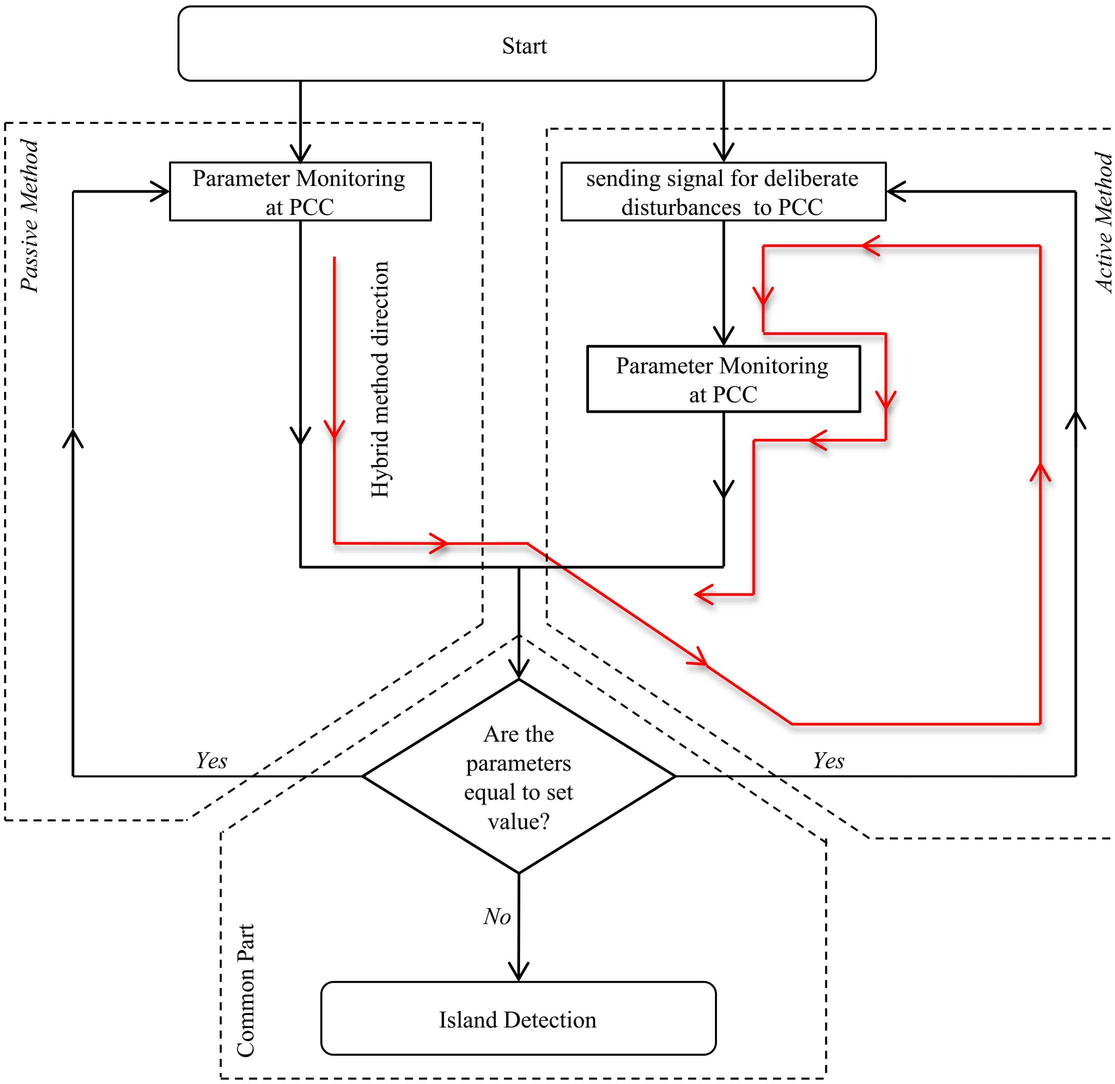


Fig. 3. Algorithm of local island-detection methods.

Table 5
Remote methods island detection characteristics.

Island detection mode	Monitored parameter	Advantages	Disadvantages	NDZ	Single DG	Multiple DG	Implementation /Speed
Transfer trip scheme	Circuit breaker statues by real time voltage	There is no NDZ	Real time monitoring of voltage can be difficult for multiple DG unit	None	✓	_	Simple/Fast
Power line communication	Continuously broadcast single to all DG units	Most effective in multiple DG case	High cost	None	_	✓	Simple/Slow

Next, the most stable sources for generating the initial power are sought. Fig. 6 presents the fundamental principles of black-start operation strategies (in red). Based on the principle, in order to prevent overloading of MSs or large frequency variations during restoration, all the loads should be disconnected as an initial step. Then, in order to avoid large transient currents or changes in power, the grid must be rebuilt in small steps [106].

After that, both controllable and non-controllable loads are connected to the network, in that order, and the loads are slowly increased [104].

The energy storage system has a very significant effect on the maintenance of power balance and on achieving acceptable voltage levels. As presented by Laaksonen et al. [102], the most effective principles for successful black-start operations are as follows: (1) rate the capacity of the storage bank. This can be estimated by considering that it must exceed the largest motor drives and converter-based DG units on the network. However, as a guideline, it should also be between 1.5 and 2 times as large as any directly connected rotating machines. (2) Any directly connected large rotating machines should be attached separately from normal loads. Also, generally speaking, the sequentially connected groups of loads should not exceed the storage available [102]. Further principles of black-start operation are presented by Moreira et al. [107].

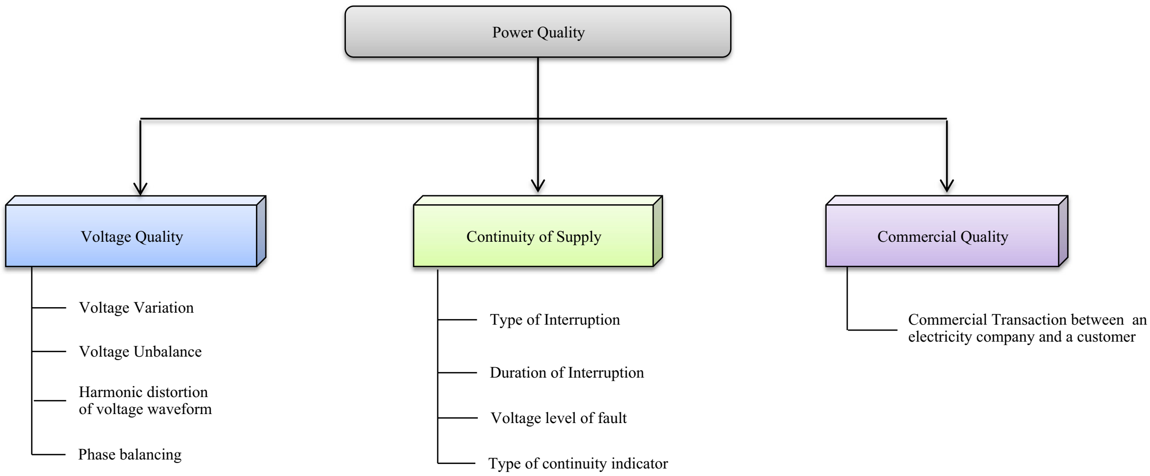


Fig. 4. Power quality coverage issues in microgrid [72].

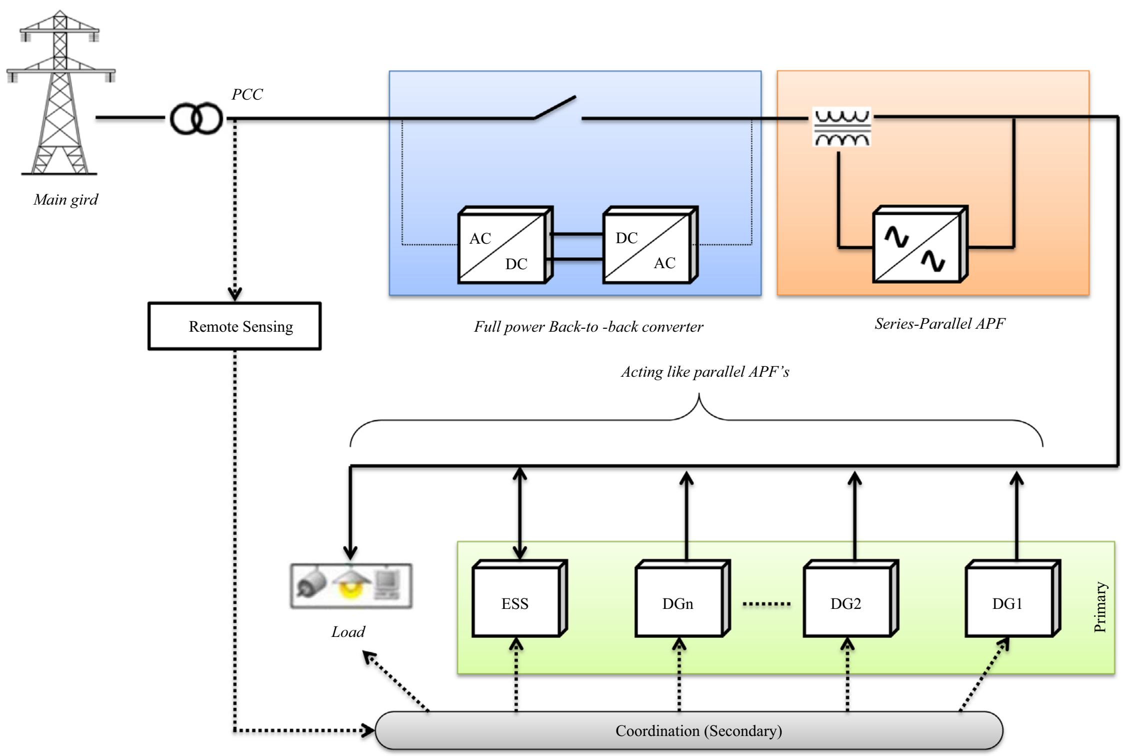


Fig. 5. Power quality scheme.

5. Fault-management principles

As discussed in the introduction, there are two different fault conditions in MGs [108,109]:

- The MG is working in grid-connected mode and a fault appears in the main grid: the MG moves to island mode using one of the methods discussed in Section 2;
- The MG is in island mode and a fault occurs inside the island area. The smallest area containing the fault should be disconnected from the rest of the system. The highest fault current, which can be supplied from the converter-based generators, is the most significant issue in this situation. Generally, these types of generators have design limitations on their converter, which causes the maximum fault current contribution to be no more than twice the rated current of the converter.

As Laaksonen et al. have presented [102], fault management in MG island mode has three parts:

- *Fault detection*: depending on which part of the system the fault occurs in, there are different methods of fault detection in island mode. This will be discussed in Section 6.
- *Fault type*: the detection of the fault type in an islanding MG is based on measurement of the phase voltages.
- *Fault location detection*: by measuring the current through the relay installed in each feeder, it is possible to find the location of fault.

Fault management in MGs is based on the exchange of information through the signals between the MGCC and the protection devices. Since protection in MGs is especially important in island mode, the DG units inside the MG must also have a backup protection setting, in

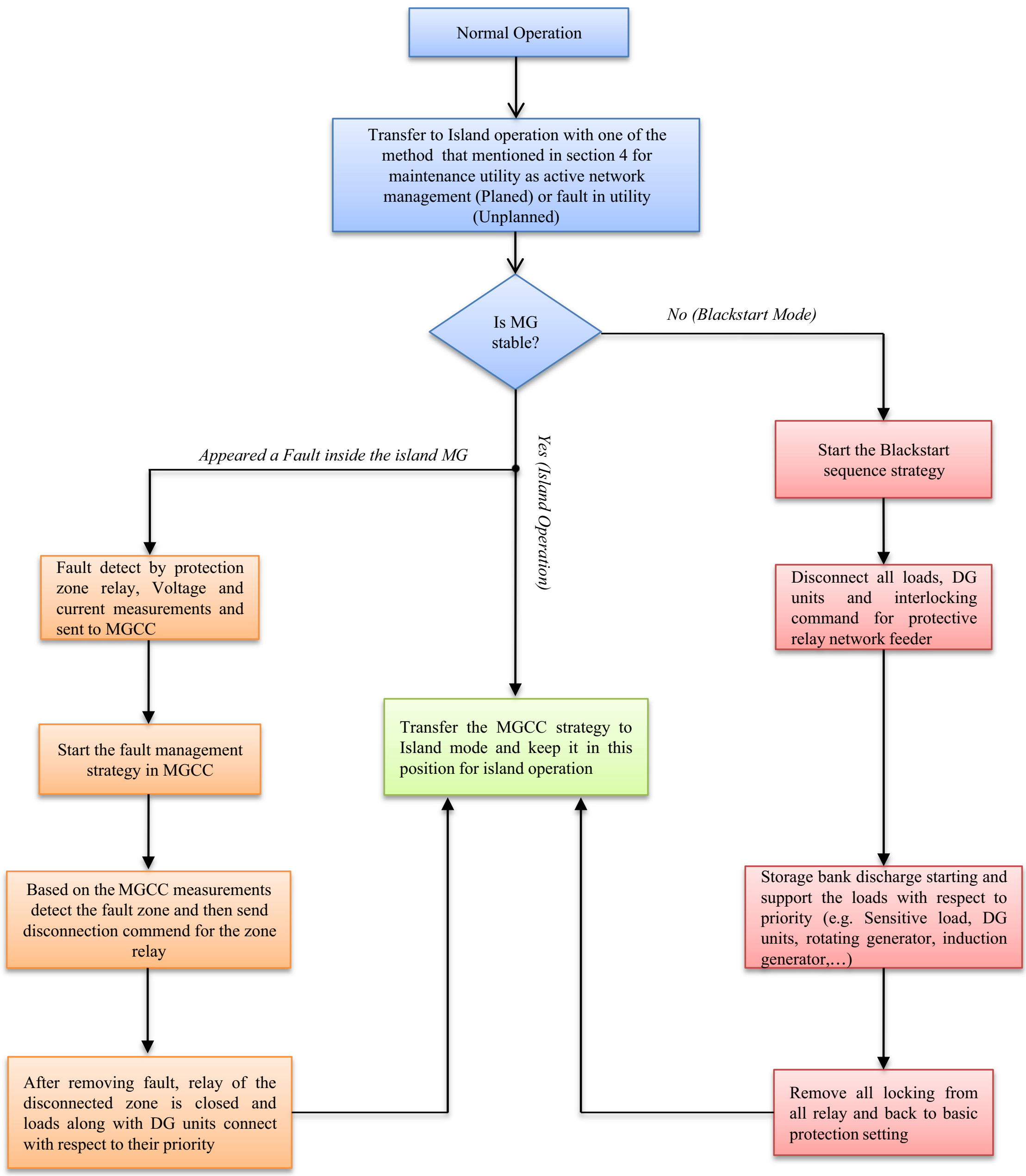


Fig. 6. Principle of black-start operation and fault management strategy. [102] (For interpretation of the references to color in this figure, the reader is referred to the web version of this article)

order to have proper operation in case the communication link with the MGCC is lost. The fault-management strategy during MG islanding is shown in orange in Fig. 6.

6. Protection

The reliability of an MG, in either grid-connected or island mode, depends crucially on the protection system employed [110]. Indeed, the protection device, protection relay, measurement equipment, and grounding are all components of the protection system.

As discussed by Justo [30], safety and fault analysis on one hand and security on the other are two important issues in protection scheme design. Moreover, in investigating these issues, some parameters should be considered. These include sensitivity, selectivity, and the speed of response [111–113].

A number of fundamental structural choices determine the speed requirements and the operational principles of MG protection. The structural choices necessary for fulfilling the speed requirements consist of switch technology, communication technology, and the size of the energy storage bank [114].

As mentioned in Section 5, two specific types of problems occur that, in general, may cause damage. The protection system should attempt to prevent these. The first condition is to maintain MG performance when a fault appears in the main grid [115]. Here, the protection relay must isolate the MG from the fault feeder. Quick switching to island mode must then be achieved through one of the methods mentioned in Section 2.

The second condition is to provide sufficient protection coordination when the system is operating in island mode. This situation removes the smallest part of the system in which the fault occurs [116,117].

The necessary steps and features of the operation of the MG under abnormal conditions arising from faults are described by the Consortium for Electric Reliability Technology Solutions (CERTS) [115]. Under the IEC/ISO 62264 standard, MG protection also has three levels. In the first level, the main structural functions of the fully developed MG include the protection of customers, DG units, and low-voltage feeder. The second level involves protection in the PCC. It should be noted that the third level of the protection also conforms to the grid-connection protection policy.

Researchers have proposed in [114,118] a smart protection system that illustrates suitable protection principles for parallel and island-operated MGs. It also acknowledges the speed requirements for protection. According to these authors, the functions needed for protection in normal and island operation are summarized in the following.

For customers, an overcurrent function is the only protection based on miniature circuit breakers (MCBs) and fuses. The relay is set based on the critical operation mode – in this case, island operation. DG unit protection is based on communication or on local measurement. In the communication method, a transfer signal is received. This could be a trip or a reconnection signal from the microgrid management system (MMS). However, local measuring methods involve voltage, frequency, and synchronization relays. These relays protect the DG unit from any over or under voltage or frequency and assist in synchronizing the unit for connection or reconnection in normal or island operation. Protection of low-voltage feeders can also be based on communications or local measurement in grid-connected mode. The communication policy is the same as for the DG unit. However, the local measuring method uses a directional overcurrent relay, which operates only when a fault appears on the low-voltage feeder. When the MG is connected to the main grid, PCC protection points employ both communication and local measurement. It is the responsibility of the protection system to transfer the disconnection signal from the MV feeder when a fault appears in the main grid. The backup for the transfer signal is the voltage relay applying the local measuring methods when a fault occurs in the main grid. The synchronism check relays used in PCCs are also employed in island-operating mode. Synchronizing the MG reconnection to the main grid according to the voltage phase and frequency difference between the MG and the utility grid is the duty of the relay [118–121].

7. Future trends and conclusion

The growth of renewable energy and its penetration into the main grids has permitted the creation of many new ideas and concepts in network management – including the microgrid. The first part of the paper attempted to propose standards (IEC/ISO 62264) for three different aspects of MG: hierarchical control, storage, and market structure. The second part presented a comprehensive review of the operational issues in MGs that have impacts on their participation in ANM. These issues included island-detection methods, black-start operations, fault-management monitoring and protection, and power quality.

In line with the growth in converter-based DG units and sensitive loads, power quality and power management are crucial for any future MGs. Several methods for power-quality compensation have been proposed in the literature. Indeed, the main performance parameters in power quality are voltage and frequency regulation, along with power sharing.

In the multiple island-detection methods used in MG operations, we noted that the speed and accuracy of detection are the main criteria. Thus, decreasing the operation time while maintaining the protection security is a crucial goal for future research into island-mode detection.

Flexible protection methods are another important issue for the MG. Protection schemes should be able to detect faults and operate in both island- and grid-connection modes. In this paper, several protection devices and measuring types required for different parts of the system have been reviewed. The study of programmable protection devices and high communication capabilities should be taken into account in working on the participation of MGs in ANM.

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